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The Effect of Mounting Vortex Generators on the DTU 10MW Reference Wind Turbine Blade

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Abstract. The aim of the current work is to analyze possible advantages of mounting Vortex Generators (VG's) on a wind turbine blade. Specifically, the project aims at investigating at which radial sections of the DTU 10 MW Reference Wind Turbine blade it is most beneficial to mount the VG's in order to increase the Annual Energy Production (AEP) under realistic conditions. The present analysis was carried out in several steps: (1) The clean two dimensional airfoil characteristics were first modified to emulate the effect of all possible combinations of VG's (1% high at suction side $x/c=0.2-0.25$) and two Leading Edge Roughness (LER) values along the whole blade span. (2) The combinations from Step 1, including the clean case were subsequently modified to take into account three dimensional effects. (3) BEM computations were carried out to determine the aerodynamic rotor performance using each of the datasets from Step 2 along the whole blade span for all wind speeds in the turbine control scheme. (4) Employing the assumption of radial independence between sections of the blades, and using the results of the BEM computations described in Step 3, it is possible to determine for each radial position independently whether it is beneficial to install VG's in the smooth and LER cases, respectively. The results indicated that surface roughness that corresponds to degradation of the power curve may to some extent be mitigated by installation of VG's. The present results also indicated that the optimal VG configuration in terms of maximizing AEP depends on the degree of severity of the LER. This is because, depending on the condition of blade surface, installation of VG's on an incorrect blade span or installation of VG's too far out on the blade may cause loss in AEP. The results also indicated that the worse condition of the blade surface, the more gain may be obtained from the installation of VG's.

1. Introduction

A Vortex Generator (VG) is an aerodynamic device, consisting of a small vane that creates a vortex. This vortex, in turn, making its way down the suction side of an airfoil, pumps the higher-velocity air from the upper segment of the boundary layer to the lower segment characterized by lower-velocity flow, thereby energizing it. If the VG's are arranged in a suitable configuration in the right position along the suction side of an airfoil, VG's can delay flow separation and aerodynamic stalling, thereby improving the lifting capacity of that airfoil. By improving aerodynamic characteristics of airfoils and wind turbine blades, VG's may increase the power output and Annual Energy Production (AEP) of wind turbines. However, even though several investigations have been carried out, e.g. [1,2,3,4,5,6], further analysis is required in order to investigate whether VG's are beneficial on a specific turbine, and if they are, on which radial stations of the blade they should be mounted on. That, in turn may depend of whether the blade surface is completely smooth or there is some sort of roughness on it. The surface of every blade deteriorates in time. The rate and type of deterioration depends on the conditions in which the blades operate. A surface of a blade operating on a desert may eat away the gel



coat relatively fast due to the contact with sand, but even the impact with raindrops cause wear of the surface over time.

The condition of blade's surface has significant impact on the aerodynamic performance as blades with rough surface enter stall faster due to the effect which roughness has on the boundary layer. In very short, one may say that the roughness disturbs the flow very close to the surface, eventually creating stall. In very short, one may also say that VG's and roughness have opposite effect on the lift curve where VG's extend the linear region and roughness shortens it. Therefore, in a case with a relatively rough surface, it may be beneficial to install VG's on the whole blade span in order to delay the angle of attack for which separation starts and thereby regain a part of the energy production 'lost' to surface roughness. The estimated loss in AEP due to roughness can be quite high. Therefore, the obtainable gain from installation of VG's in these cases can be quite significant.

The situation is often quite different in case of (new) blades with smooth surfaces. If the blade is well designed, the whole outer part of the blade, which account for the vast majority of the power production, is not entering stall. Adding VG's to that part of the blade will in this case only decrease the power production due to the extra added drag due to the VG's themselves. However, the root sections of wind turbine blades are relatively thick in order to transmit the very large bending moments generated at the outer parts of the blade. This is aerodynamically unfavorable because these thick airfoils stall much earlier than their thinner counterparts. This may be at least partly addressed by mounting VG's at the inner part (approx. out to 30%) of the blade span in order to reattach the boundary layer and increase the energy production stemming from the inner blade sections. Different sources report different gains in AEP where the upper limit appears to be around 2%.

The aim of the current work is to analyze possible advantages of mounting VG's on the DTU 10 MW Reference Wind Turbine [7]. The project aims at investigating at which radial sections of the blade it is most beneficial to mount VG's in order to increase The AEP for blades with two different levels of surface roughness as well as for the smooth surface case.

2. Methods

2.1. Analysis procedure

The aim of the current work is to analyze possible advantages of mounting VG's on the DTU 10 MW Reference Wind Turbine. The primary tools used in the project are engineering models for the effect of the VG's and surface roughness developed in the present work by Gaunaa and described herewith, three-dimensional effects by Bak et al. [8], and the Blade Element Momentum based analysis and optimization code HAWTOPT by Fuglsang [9].

The present analysis was carried out in several steps, listed below:

1. The clean two dimensional airfoil characteristics were first modified to emulate the effect of all possible combinations of surface roughness and VG's (1% high at suction side $x/c=0.2-0.25$) along the whole blade span.
2. The resulting polars, including also the clean case, were modified to account for three dimensional effects.
3. BEM computations were carried out to determine the aerodynamic rotor performance using each of the datasets from Step 2 along the whole blade span for all wind speeds in the turbine control scheme. The turbine blades were not pitched to reduce the angle of attack until the rated power of 10 MW was reached when increasing the wind speed.
4. Employing the assumption of radial independence between sections of the blades, and using the results of the BEM computations described in Step 3, it is possible to determine for each radial position independently whether it is beneficial to install VG's in the clean and Leading-Edge-Roughness (LER) cases, respectively. Note that the aerodynamics of a blade section is not entirely radially independent from other sections whereas such assumption is always present in BEM. Further, airfoil characteristics are typically obtained in a wind tunnel or by computations, independent of other airfoils. The present analysis, based on the assumption of radial

independence, seems to be an optimal compromise between computational efficiency and reliability of the results. Alternatively, a classic optimization problem could be set up on the expense of the problem's complexity and computational efficiency. In such, an optimization algorithm would determine the position of VG's on the blade and use the BEM code to obtain the corresponding aerodynamic response. Then, the effects of blade deflection could be included.

2.2. Description of the method to modify aerodynamic data to emulate the effect of Vortex Generators

Analysis of measurements of various airfoils with and without VG's in the VELUX open-jet wind tunnel at $Re=1.6 \times 10^6$ [10, 11, 12] and in the Stuttgart Wind Tunnel at $Re=3.0 \times 10^6$ [13] have shown that the main effects of VG's on the lift coefficients on 2D airfoils can be modeled in a simple way using the lift decomposition used in several dynamic stall models. In this decomposition, the actual lift coefficient is a weighted sum of a fully attached lift coefficient and a fully stalled lift coefficient. The weight factor is the separation function, which is 1 for attached flow and 0 for fully stalled flow. The lift is therefore written as:

$$C_l(\alpha) = C_{l,att}(\alpha) f(\alpha) + C_{l,fs}(\alpha) (1 - f(\alpha)) \quad (1)$$

where α is the angle of attack, $C_l(\alpha)$ is the resulting lift coefficient, $C_{l,att}(\alpha)$ is the fully attached lift coefficient, $C_{l,fs}(\alpha)$ is the fully separated lift coefficient, and $f(\alpha)$ is the separation function. Hansen et.al [14] explains in detail how the decomposition is performed in the Risø BL Dynamic stall model. In the dynamic stall models, the key effect in dynamic behavior of the lift in stall is essentially modeled by lagging the separation function in time using for instance filters in time. In the present case we are not concerned with the temporal behavior of the coefficients, but instead how adding VG's to an airfoil, and thereby modifying the boundary layer to delay stall, can be modeled. From analysis of the measured airfoil data it was observed that the fully attached lift coefficients in the decomposition were scarcely affected by the addition of the VG's to the airfoil. Also the fully separated lift coefficient remained relatively unchanged by the addition of the VG's, so essentially only the separation function was altered by the addition. This finding therefore suggests that the effect that VG's have on the lift coefficient could be modeled by decomposing the lift in the two separate lift coefficients (attached and fully stalled parts) and the separation function, and then changing the separation function to take into account for the effect of the VG's on the resulting lift. The modelled lift coefficient curve is then obtained from the fully attached and fully stalled curves from the baseline non-VG case by use of the modified separation function.

The lift part of the VG model only uses a single parameter – the angle offset that the separation function is to be shifted with between $f=0.7$ and $f=0.3$. The angle of attack where the lift starts deviating from the fully attached region, $f=0.999$, stays the same in the VG case, as does the angle of attack where the flow is fully separated $f=0$. The separation function offset angle is most likely a function of many parameters: airfoil type, airfoil relative thickness, type/size/position of the VG's, Reynolds number, turbulence intensity in the oncoming flow, and possibly other parameters. One way of obtaining a plausible value for this angle offset is to investigate airfoils of the same relative thickness with measurements with and without VG's at conditions (Reynolds numbers and turbulence intensity) comparable to those at which VG's should be modeled. In the present work, measurements carried out in the VELUX wind tunnel [10, 11, 12] ($Re=1.6$ million, 1% turbulence) and in the wind tunnel of the University of Stuttgart ($Re=3$ million, 0.02%-0.05% turbulence) [13] were used to determine suitable angle offsets.

The method of taking into account the VG's in the drag coefficient response uses the same coefficient as the lift. Since the addition of the VG's introduces additional drag on the VG's themselves, and additional drag due to energizing the boundary layer, there is a drag penalty added in the linear region $\Delta C_d(\alpha) = f(\alpha) \Delta C_{d,VG}$ where ΔC_d is the resulting drag coefficient increase, f is the separation function, and $\Delta C_{d,VG}$ is the drag offset level. Apart from this, the drag model “stretches” the original drag contribution according to the separation function such that the drag in the VG case at some angle of

attack is equal to the drag that the original airfoil has at the angle where the separation function has the same value. This is done because the majority of the drag value in stall and partly stalled conditions is associated with separation, so when the VG's delay separation, then also the drastic increase of drag associated with this is delayed. In addition to the part of the drag corresponding to the pressure field of the reference "clean" case, the VG equipped case has higher lift coefficients (and thereby generally lower pressures on the suction side) than that of the baseline case for the same value of the separation function. Therefore, an additional drag term is added in the VG simulation which depends on the difference between the VG lift and the baseline lift, as well as the separation function. Figure 1 shows a typical input and output obtained using the VG model, i.e. showing that the model predicts the performance as expected. The addition of the VG's resulted in an increase of maximum lift and an increase of drag in the linear region. The result is also supported by the behavior observed in the analyzed measurements, i.e. drag of the case with VG's is lower than the reference case in the angle of attack regions where the reference case stalls more than the case with VG's. Note that in those angle of attack regions it is most beneficial to use VG's on wind turbine blades.

The present engineering model used in the present work does not affect the aerodynamic moment coefficients. However, the moment coefficients are not used in the BEM computations used in the present work.

The relative chordwise positions, x/c , of the modeled VG's with $h/c=1\%$, where h is the height of the VG, was at the position at which the aforementioned wind tunnel tests show good performance of VG's, i.e. $x/c=0.3$ for $t/c<30\%$, $x/c=0.25$ for $t/c>36\%$, and linearly interpolated for other airfoil thicknesses. The analysis is essentially based on the VG configuration described by Fuglsang et al [10, 11, 12]. General information regarding relative dimensions and layout of VG's was given by Hoerner [18].

2.3. Emulation of rough airfoil data from clean airfoil data

The usual way to emulate the effect of airfoil surface roughness in wind tunnel environments are to add standardized roughness elements on specified locations of the otherwise clean airfoil surface. One widely used method, termed Leading Edge Roughness (LER) in this work, is to add high turbulator 90° zigzag tape (originally intended for use on glider planes) at 5% of the chordlength from the leading edge along the suction side of the airfoil, and 10% of the chordlength from the leading edge along the pressure side. The height of the zigzag tape is $h = 0.38\text{mm}$, its opening angle is 60 degrees, and the tape extends 11mm in the streamwise direction. This type of roughness has a relatively big impact on the performance of the airfoils. Analysis of the measurement data obtained from the Stuttgart wind tunnel at $Re=3\times 10^6$ [13] where the chordlength of the airfoil was 600 mm shows that the addition of VG's to cases with LER results in a much higher increase in lift performance due to the VG's than in the cases with clean blades. Additionally, the added VG-penalty on the drag in the linear region may be relatively less prominent than in the corresponding clean case. The experimental results also show clearly that the "damage" imparted to the maximum lifting performance by the LER can be more than compensated by using VG's. The payment for this is a relatively small increase in drag in the linear region. The last thing observed was that like in the LER-only cases (without VG's), the LER+VG cases showed the angle offset which is therefore assumed to be linked to the LER. Since the LER+VG case performance looked more like the clean case than the LER case, a slightly modified version of the VG model is used to generate LER+VG data. The additional modification needed is only the simple angle offset due to LER.

The parameters for the airfoils used in the modelling of LER and VG's are based on trends observed in the Velux [10, 11, 12] and Stuttgart [13] measurements. The parameters are presented in Table 1. The levels of the surface roughness were named LER1 and LER05 where LER1 corresponds to a degradation of the airfoil performance corresponding to the quite severe LER used in the wind tunnel applications and LER05 corresponds to less pronounced surface roughness than LER1.

Table 1: Parameters used for modelling of Leading Edge Roughness (LER) and Vortex Generators (VG's)

Thickness	24%			30%			36%			48%		
Case	AoaOffset	DeltaAoaSepf	DeltaCdLin	AoaOffset	DeltaAoaSepf	DeltaCdLin	AoaOffset	DeltaAoaSepf	DeltaCdLin	AoaOffset	DeltaAoaSepf	DeltaCdLin
Clean+VG	0.0	5.4	0.004	0.0	6.5	0.005	0.0	6.5	0.006	0.0	6.5	0.006
LER1+VG	1.0	2.9	0.010	1.0	3.5	0.013	1.0	4.5	0.018	1.0	4.5	0.022
LER05+VG	0.5	4.2	0.007	0.5	5.0	0.009	0.5	5.5	0.012	0.5	5.5	0.015
LER1	1.0	-4.1	0.006	1.0	-4.5	0.008	1.0	-7.0	0.014	1.0	-7.0	0.014
LER05	0.5	-2.0	0.003	0.5	-2.3	0.004	0.5	-4.5	0.070	0.5	-4.5	0.070

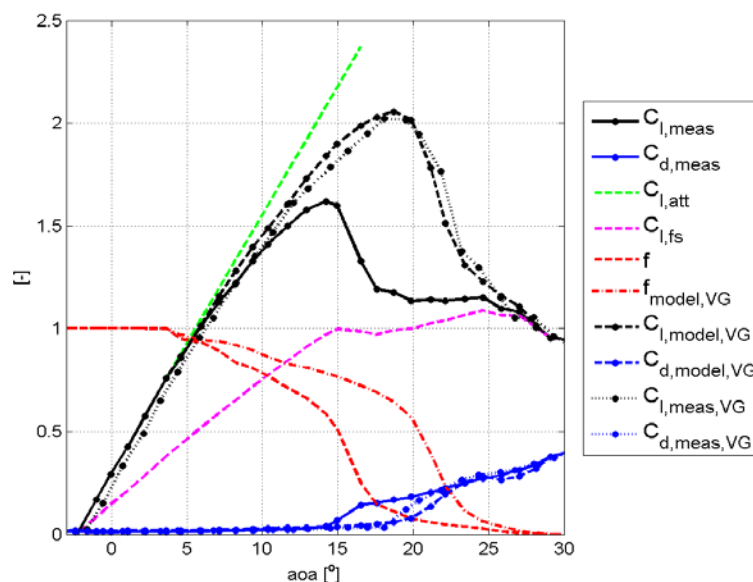


Figure 1: Comparison of the present VG modeling method and experimental results [11] for the Risø-B1-24 airfoil at $Re=1.6 \cdot 10^6$. The modelled data (dashed) are obtained from the baseline measured data (full) using parameters [AoaOffset=0° DeltaAoaSepf=5.5° DeltaCdLin=0.005]. Measured data with VG's mounted at $x/c=0.2$ are shown with dotted lines.

2.4. Description of the method to 3D correct data

The airfoil lift coefficients (except for the cylinder part) were 3D corrected according to Bak et al. [8]. This method is based on the difference between the 3D pressure distributions as measured on a wind turbine in operation and 2D pressure distributions as measured in a wind tunnel. Thus, this method is in contrast to all other 3D correction methods known to the authors, which are based directly on the lift curves.

3. Results

In the present study, two levels of surface roughness were used in addition to the aerodynamic coefficients of the clean DTU 10 MW Reference Wind Turbine blade [7], which is equipped with a family of FFA airfoils [19]. Examples of the lift and drag coefficients of the clean airfoils as well as the LER1 and LER05 cases are presented in the figures below together with the corresponding coefficients modified to take into account the influence of VG's. Figure 2 presents the lift (a) and drag (b) coefficients, respectively, with and without VG's, used for the case with the clean, non-contaminated blade. Note that the baseline aerodynamic coefficients of the 36% and 48% thick airfoils used in the present work are equipped with Gurney Flaps.

As expected, VG's modelled on the airfoils delayed stall and therefore lengthened the angle of attack region in which the slope of the lift coefficient curve is approximately equal to 2π . Further, the addition of the VG's marginally increased the drag coefficient in the angle of attack region in which the flow over the airfoil not equipped with VG's is attached, and decreased the drag coefficient in the angle of attack band above the stall of the airfoil not equipped with VG's. As in the case of the clean airfoils, VG's modelled on the airfoils with LER1 delayed stall, increased maximum lift and increased the drag in the linear region compared to the non VG case. It is seen that installing VG's on a blade with surface roughness may to some extent mitigate the unfavorable consequences of the surface roughness.

Figure 4 presents examples of the lift (a) and drag (b) coefficients, respectively, with and without VG's, used for the LER05 case.

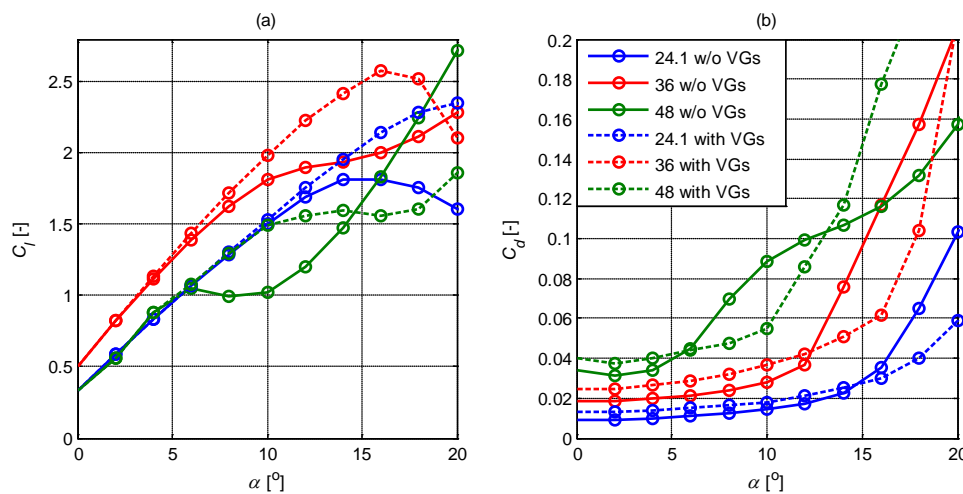


Figure 2: Examples of the lift (a) and drag (b) coefficients of the FFA [19] airfoils used on the DTU 10MW Reference Wind Turbine blade [7], respectively, with and without VG's, used for the case with the clean, non-contaminated blade

Figure 3 presents the lift (a) and drag (b) coefficients, respectively, with and without VG's, used for the LER1 case, i.e. the one with more pronounced surface roughness. The main difference between Figure 2 and Figure 3 is that surface roughness significantly decreased performance of the airfoils, as presented in Figure 3, causing them to stall earlier.

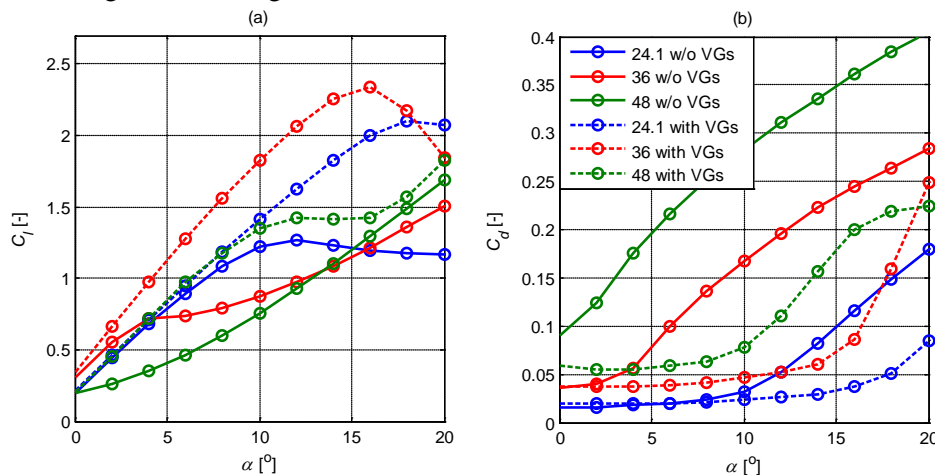


Figure 3: The lift (a) and drag (b) coefficients of the FFA [19] airfoils used on the DTU 10MW Reference Wind Turbine blade [7], respectively, with and without VG's, used for the LER1 case, i.e. the one with more pronounced surface roughness

The influence of VG's on the aerodynamic coefficients is similar as in the previous two cases, i.e. VG's delayed stall of the modelled airfoils. The level of surface roughness and the aerodynamic coefficients presented in Figure 4 may be thought of as being in-between the clean coefficients presented in Figure 2 and the LER1 coefficients presented in Figure 3.

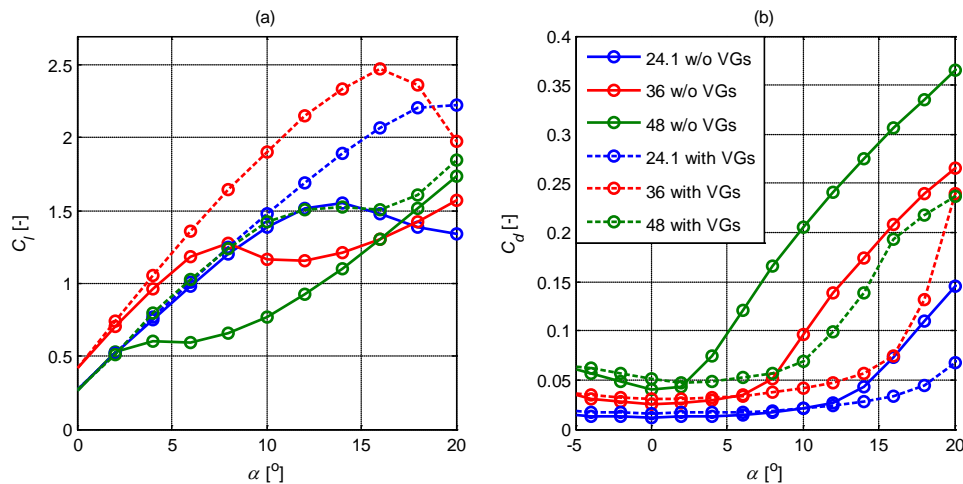


Figure 4: The lift (a) and drag (b) coefficients of the FFA [19] airfoils used on the DTU 10MW Reference Wind Turbine blade [7], respectively, with and without VG's, used for the LER05 case, i.e. the one with less pronounced surface roughness

All three sets of coefficients together with the operational data of the DTU 10 MW RWT [7] were used in a set of BEM computations. The analysis was carried out with wind shear equal to 0.2, and the Weibull shape parameter equal to 2. The results from the BEM computations were analyzed and, in Figure 5 (a), the relative increase in the Annual Energy Production (AEP) is presented as a function of the radial position until which VG's were modelled. Note that the solid lines refer to the original operational characteristics of the DTU turbine where the maximum tip speed (MTS) of the turbine was equal to 90 m/s. The dashed lines refer to edited characteristics where MTS was equal to 70 m/s. This means that in the latter, the constant RPM was obtained by the turbine before the rated power. Although MTS of 70 m/s is artificially low, it is common for wind turbines to obtain constant RPM before obtaining rated power. With this respect, the DTU turbine is different as both are obtained simultaneously, and the reason for introducing this gap in the present work was to show how VG's may influence turbines with such gap. According to the presented results, in order to increase AEP for the clean blades, VG's would need to be mounted from 19 m to 24 m of blade span for the case with 90m/s MTS. However, this would only correspond to a marginal increase in AEP of 0.1%. Remember that the curves show the relative AEP benefit of adding VG's from the root to a certain blade span. Mounting VG's from the root to 19 m blade span would decrease AEP in the clean case. However, since in the BEM analysis, and to some extent in real life, the radial sections are independent, only mounting VG's from 19 to 24 m, would increase AEP.

In the LER05 case, installing VG's from 14 m to 30 m of blade span would increase AEP by 1.4% in the case with 90 m/s MTS. In the case with 70 m/s MTS, installing VG's from 14 m to 34 m would increase AEP by 1.8%. In the LER1 case, installing VG's from 11 m until the tip would increase AEP by 4.8% in the case with 90 m/s MTS, and by 10.1% in the case with 70 m/s MTS. However, installing VG's from 11 m to only 40 m of blade span would already increase AEP by 3.6% in the case with 90 m/s MTS, and by 6.4% in the case with 70 m/s MTS. In order to present the problem in a broader context, Figure 5 (b) shows the absolute values of AEP as a function of the radial position until which VG's were modelled.

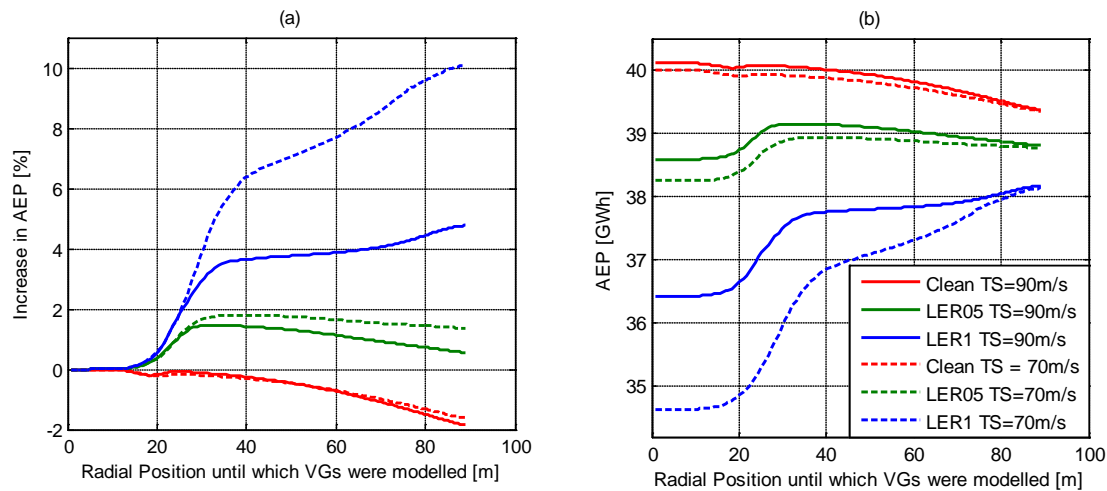


Figure 5: (a) An increase in Annual Energy Production (AEP) of the DTU 10 MW RWT [7] plotted as a function of the radial position, starting from the root, until which Vortex Generators (VG's) are modelled, relative to AEP of the blade without VG's (b) Annual Energy Production (AEP) of the DTU 10 MW RWT [7] plotted as a function of the radial position, starting from the root, until which Vortex Generators (VG's) are modelled

Figure 5 (b) shows that reducing MTS of the turbine reduces AEP. Further, the worse surface condition of the blades, the higher loss in AEP is introduced by the same reduction of MTS. Additionally, the further out on the blade VG's are installed, the smaller the AEP gap between the cases with different MTS values is.

In order to shed more light on the details leading to the aforementioned AEP predictions, Figure 6 presents the power curves corresponding to the clean blade, the blade with LER05 and LER1, and the power curves corresponding to the most beneficial configuration of VG's according to AEP, for the wind speeds up to 14 m/s and 90 m/s MTS. Above 14 m/s wind speed, up to the cut-out wind speed of 25 m/s, all the power curves are identical, maintaining the rated value of 10 MW.

The figure indicates that significant surface roughness (LER1) may correspond to a large degradation of the power curve which to some extent may be mitigated by installation of VG's. Note that the curve representing the clean blades with VG's was omitted.

The present results also indicated that in order to install VG's so that an increase in AEP is observed, modelling of VG's should be carried out taking into account the actual condition of the blade surface. This is because, depending on the condition of blade surface, installation of VG's too far out on the blade may cause loss in AEP caused by the unwanted additional drag of the VG's in cases where the roughness is not severe enough to require "repair" from the VG's.

The results also indicated that the worse condition of the blade surface, the more gain may be obtained from the installation of VG's. Analysis of the results presented in Figure 5 led to the conclusion that it is possible to install VG's on clean blades in such a configuration that they would not reduce the energy production of the clean blades while they would mitigate some of the negative effects of the deterioration of the blade surface in time. In order to do so, the VG's would need to be installed from 20 m to 32 m of blade span since in such a configuration they would not reduce AEP of the clean blades while they would mitigate some of the negative effects of surface roughness that would occur over time. This would correspond to a 4% recovery of the AEP in the LER1 case assuming 70 m/s MTS. Note that the DTU 10 MW Reference Wind Turbine, because of its design characteristics, may be relatively insensitive to blade surface roughness. Turbines operating closer to the angle of attack corresponding to stall would likely be more sensitive to blade surface roughness. Therefore, those turbines, with surface roughness, would possibly benefit more from the installations of VG's.

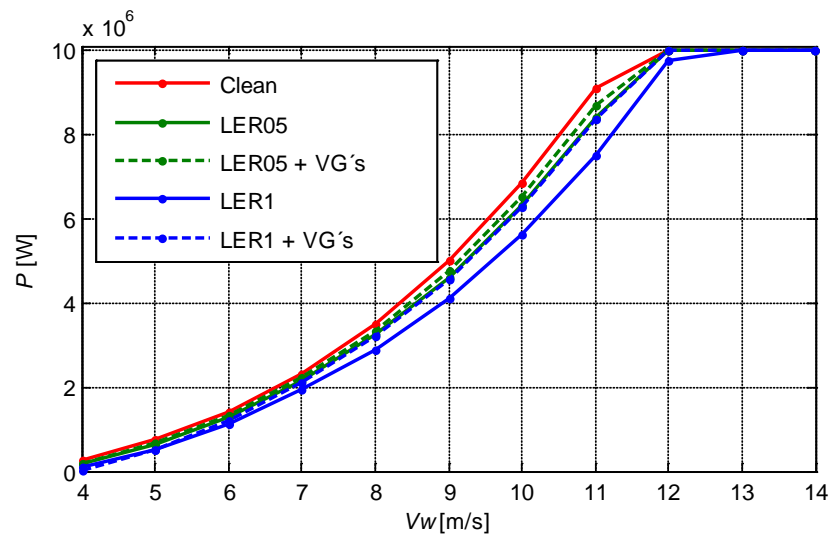


Figure 6: Power curves of the DTU 10 MW RWT [7] corresponding to the surface roughness and Vortex Generators (VG's) cases modelled in the present work

4. Conclusions

The aim of the current project was to analyze possible advantages of mounting VG's on a wind turbine blade. Specifically, the project aimed at investigating at which radial sections of the DTU 10 MW Reference Wind Turbine blade it is most beneficial to mount VG's of height in order to increase AEP under realistic conditions. The present analysis was carried out in several steps: (1) The clean two dimensional airfoil characteristics were first modified to emulate the effect of all possible combinations of VG's (1% high at suction side $x/c=0.2-0.25$) and two LER values along the whole blade span. (2) All possible combinations from Step 1, including also the clean case, were subsequently modified to take into account three dimensional effects. (3) BEM computations were carried out to determine the aerodynamic rotor performance using each of the datasets from Step 2 along the whole blade span for all wind speeds in the turbine control scheme. (4) Employing the assumption of radial independence between sections of the blades, and using the results of the BEM computations described in Step 3, it was determined for each radial position independently whether it is beneficial to install VG's in the clean and LER cases, respectively.

Two values of MTS of the turbine were investigated, i.e. the original of 90 m/s, and the artificial of 70 m/s. Additionally, two cases of surface roughness were investigated along with the clean surface case. LER1 corresponded to a severe surface roughness and LER05 to a less severe surface roughness. Compared to the clean surface case, the LER05 case corresponded to a 3.5% loss in AEP whereas the LER1 case corresponded to a 9.0% loss, both for 90 m/s MTS without any VG's. The computational results for the clean surface case showed that it is practically not possible to increase AEP further by the addition of VG's. In the less severe roughness case (LER05) the optimal configuration of the VG's was to mount them between 16% and 38% of the blade radius assuming 70 m/s MTS. This resulted in an increase of AEP by 1.8%. For the severe roughness case (LER1) the increase in AEP was 4.8% assuming 90 m/s MTS, and 10.1% assuming 70 m/s MTS. For those cases the optimum VG configuration was to mount them all the way from 12% radius to the tip. Alternatively for the LER1 case, the VG's could be installed from 12 % to 45 % in order to increase AEP by 3.6% in the 90 m/s case, and by 6.4% in the 70 m/s case. In order not to lose AEP while the blade surface is in good condition but to mitigate some of the negative effects of surface deterioration over time, the VG's would need to be installed between 22% and 36% of blade radius. This would correspond to a 4% recovery of AEP in the LER1 case assuming 70 m/s MTS. The results indicated that surface roughness may correspond to a large degradation of the power curve which to some extent may be mitigated by installation of VG's. The present results also indicated that, generally, in order to install VG's so that

an increase in AEP is observed, modelling of VG's should be carried out, preferably taking into account the actual condition of the blade surface. This is because installation of VG's on an incorrect blade span or installation of VG's too far out on the blade may cause even a loss in AEP due to the addition of the extra drag associated with the VG's for conditions where the non-VG airfoil does not stall. The results also indicated that the worse condition of the blade surface, the more gain may be obtained from the installation of VG's. This gain may be larger for the turbines that reach constant RPM before they reach rated power. In future work, a similar study to the one presented in this paper should be carried out on other turbines in order to further investigate how different turbine designs influence the turbines' sensitivity to surface roughness and to what extent it may be mitigated by VG's.

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